Collective ECC Cusp in Many-Electron Continua in Strong Field Heavy Ion Collisions

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We have measured doubly differential cross sections for continuum electron emission induced by $I^{23+, 26+}$ and $F^{8+, 9+}$ projectiles incident on He and Ar targets. We find that the angular distribution of electrons emitted for multiple ionization of the target and detected in coincidence with the charge state of the recoiling ions exhibits a strong enhancement of emission in a narrow forward cone. At high emission multiplicities electrons in momentum space are surprisingly found to be concentrated around the projectile Electron Capture to the Continuum ($v_e = v_{Proj}$) ECC-Cusp– which is inconspicuous for single ionization of the target but then rises to be the prominent feature in the electron spectra of higher multiplicities.

Electrons emitted in the target zone in a plane containing the beam direction (azimuth $\varphi = 0^0$) and with polar angles $\theta = 0^0$ to $\theta = \pm 180^0$ with respect to the beam direction are energy analyzed in a toroidal electrostatic electron spectrometer and detected with a channelplate detector equipped with a 2D position sensitive wedge and strip anode. Recoil ions are extracted from the target zone using a fast HV pulsing technique and are detected using a channelplate detector also equipped with a 2D position sensitive wedge and strip anode/1/.

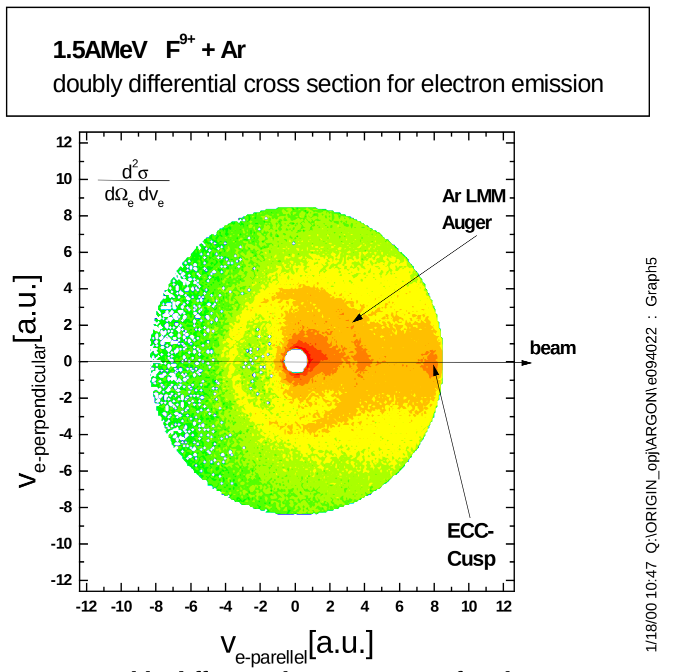

Fig. 1: Double differential cross sections for electron emission for 1.5AMeV F^{9+} + Ar for electron velocities between 0.6 and 8.2 a.u.

The simultaneous detection of electrons from all polar angles is illustrated in fig. 1. It shows the momentum space doubly differential cross section (DDCS) $d^2\sigma/(dv_e d\Omega_e)$ for electron emission for 1.5AMeV F^{9+} (v_{Proj} = 7.78 a.u.) impinging on an Ar target, no coincidence condition is applied. Electrons with velocities between v = 0.64 a.u. and 8.2 a.u. and emission angles between $\theta = 0^0$ and $\pm 180^0$ with respect to the beam direction are seen. The prominent broad ring with $v_e \approx 4.0$ a.u. consists of Ar LMM satellite Auger lines emitted by Ar recoil ions in various charge states. The projectile ECC peak of electrons with very low velocity with respect to the projectile at a laboratory electron velocity $v_e = v_{proj}$ = 7.78 a.u. and $\theta = 0^0$ with respect to the beam direction can also be clearly seen.

In fig. 2 double differential cross sections DDCS $d^2\sigma/(dv_e d\Omega_e)$ for electron emission coincident with recoiling Ar ions in 3 selected final charge states q_R = 1+ to q_R = 12+ are compared for 0.35AMeV I^{23+} , i.e. a collision with Sommerfeld parameter q_{Proj}/v_{Proj} = 6.13.

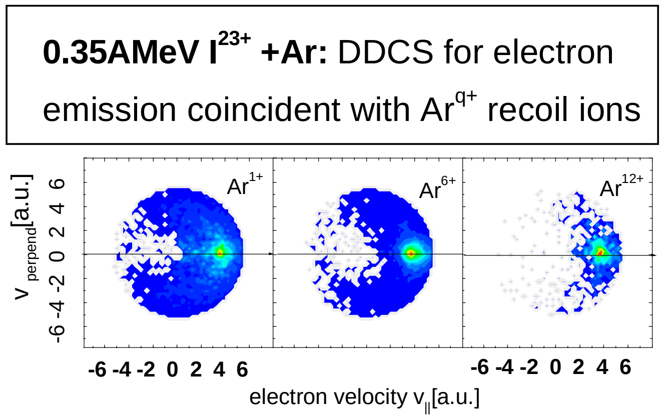

Fig. 2: Doubly differential cross section for electron emission coincident with recoil ions in final charge states Ar^{1+}, Ar^{6+} and Ar^{12+} for 0.35AMeV I^{23+} + Ar collisions.

The ECC Cusp of electrons captured into low momentum continuum states of the projectile is the tall, slender peak easily identifiable at $v_{e\|} = v_{Proj}$ and $v_{e\perp} = 0$ in all coincident electron spectra up to those coincident with Ar^{12+}. In the spectra of electrons coincident with high recoil charge states most electrons lost by the target and not captured into the projectile bound states have condensed to a drop around the ECC Cusp-location in momentum space whose radius is decreasing slightly with increasing number of released electrons down to FWHM ≈ 1 a.u. An increasing asymmetry of the Cusp emphasizes its high momentum side while electron emission with momenta below the Cusp appears to be distinctly disfavored for higher multiplicities.

The dominance of electrons condensing onto the ECC-Cusp in the continuum allows a simple argument, based on momentum transfer to electrons in the ionization process, to be made on the observed variation of the coincident cross section with recoil charge state.

In the incoming channel of the collision the loosely bound electrons of the target have a momentum of typically 3.75 a.u. as seen by the projectile incident with 0.35AMeV. For a single active electron of the target to be captured into a projectile

ECC-continuum state with final momentum $p_e \approx 0$ with respect to the projectile it must undergo a violent collision with momentum transfer $\Delta\mathbf{Q}_1 = v_{Proj}$ /2/.

An independent-particle model of multi-electron ECC Cusp production then implies that all electrons found in the ECC Cusp will individually have undergone a high momentum transfer collision with the projectile. A multiple independent–electron ECC cross section for j electrons should follow $\sigma_j(ECC) \sim 1/(\Delta\mathbf{Q}_j)^n$ with $n \geq 2$ in a perturbation treatment and would result in a very steep decrease of $\sigma_j(ECC)$ with j, i.e. also with recoil charge state q_R, as the minimum momentum transfer $\Delta\mathbf{Q}_j$ for j electrons out of q_R transferred into the ECC-continuum independently is $\Delta\mathbf{Q}_j = \max\left(\sum_{i=1}^{j} E_B(i)/v_{Proj},\ j\bullet v_{Proj}\right)$ with $E_B(i)$ the binding energy of the i-th electron/3/. $\Delta\mathbf{Q}_j$ is obviously increasing with the number of electrons in the continuum.

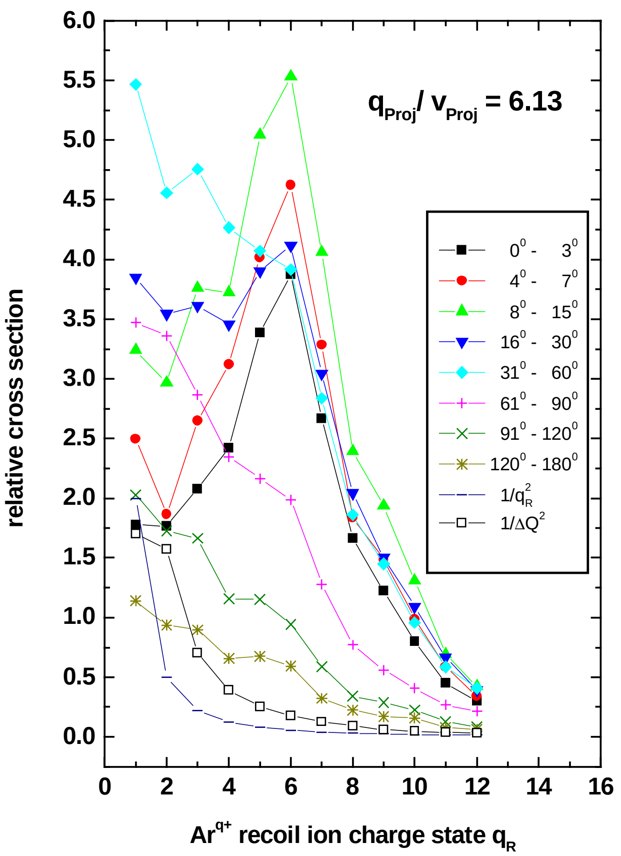

Fig.3: Coincident multi-electron emission in selected polar angle detection windows for 0.35AMeV I^{23+} + Ar as function of the recoil ion charge state. Open squares result from the estimate of the minimum momentum transfer for multiple ECC. Graphs for individual sectors are not to be compared with each other on an absolute scale as they carry different weights according to the window width.

This, however, is at variance with the observed non-monotonic variation of the experimental cross sections with recoil charge state(fig. 3) for large perturbations as given by the incident 0.35AMeV I^{23+}projectile. For weak perturbations, e.g. with an incident 1.5AMeV F^{9+} projectile, we observe a near-monotonous, strong decrease with q_R uniformly in all electron emission angle sectors/1/.

In fig. 3 we compare for selected polar angular sectors the dependence of the coincident electron emission cross section on the charge state q_R of the recoiling target ion for a strong perturbation s = 6.13 (incident 0.35AMeV I^{23+} projectile). With strong perturbations the contributions from multiple ionization(i.e. $q_R \geq 2$) clearly dominate over single ionization (see fig. 3) for the sectors of forward electron emission up to 30^0 with respect to the beam. The cross sections for sectors up to 30^0 exhibit uniform increases up to $q_R = 6$, steepest for the 0^0 to 3^0 sector containing the ECC Cusp, and most gently for the 15^0 to 30^0 sector. The sectors for angles larger than 30^0 exhibit a monotonous decrease of the relative cross section with recoil charge state q_R as is also the case for systems investigated for low perturbation/1/. We also find that the forward enhancement of electron emission with increasing recoil charge state is remarkably strong: the intensity in the sector 0^0 – 3^0 normalized to the backward sector 120^0- 180^0 increases monotonically by about a factor 10 when going from Ar^{1+} to Ar^{10+}/1/. The slope of the cross section following from the independent particle model using simple estimates for $\Delta\mathbf{Q}_j$ clearly disagrees with the experiment even when the multiplicity of emission is taken into account(see fig. 3). The observed cross sections appear to suggest that for an increasing number of electrons j emitted into the ECC an effectively smaller momentum transfer $\Delta\mathbf{Q}_j$ is required than for single electron transfer into the ECC. This, however, is not compatible with an independent-electron model of ionization into the ECC Cusp.

The results we obtain here in the regime of strong perturbation and up to 12-fold electron loss of the Ar target suggest a more generalized view, beyond the independent particle picture, of the dynamics of multiple ionization. We believe that we observe a collective interaction of a swarm of quasi-free electrons in the strong transient field of the highly charged projectile. This results in "capture cooling" of electrons as seen in the projectile frame. The term is coined in analogy to evaporative cooling; however, the role of the hot, evaporating particles is surmised to be assumed by those electrons which acquire in the elastic electron-electron collisions a matching momentum suited for quasi-resonant capture into a bound state of the projectile while the remaining *electrons "cool" into states of very low momentum in the projectile frame continuum.*

In order to corroborate this hypothesis we plan to extend the range of collision times at the highest perturbation strength covered in the present experiment: with high Z projectiles from the UNILAC interaction times can be reduced by approximately a factor 4 while maintaining the same high perturbation strength. This shortens the available cooling time and so changes the width of the ECC-continuum.

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